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RECIRCULATING ELECTROSTATIC ACCELERATORS

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RECIRCULATING ELECTROSTATIC ACCELERATORS

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Abstract

A 3 MeV electrostatic accelerator has been modified for high electron current operation using beam recovery. In a simple configuration, a maximum of 99.4% of a 1.25 Ampere electron beam has been recovered. In a more complex beam transport system that includes a permanent magnet undulator as much as 95% of the beam has been recovered. These devices are ideally suited to drive efficient free-electron lasers. Beam quality and beam recovery measurements are presented here.

Introduction

Free-electron lasers (FELs) demand ampere level, high quality, monochromatic electron beams for their operation. Quantitatively, these requirements can be derived from the electron energy γmc^2, the number of undulator periods N, and the on-axis undulator magnetic induction field B. For example, a constant period undulator FEL operating in the single particle regime, imposes on the electron beam the following requirements :

$$\frac{\Delta\gamma}{\gamma} \leq 1/2N , \qquad \theta \leq 1/\gamma\sqrt{N} , \qquad r_0 \leq mc/eB\sqrt{N} \qquad (1)$$

where the first term on the left of equation (1) describes the maximum allowed electron longitudinal momenta spread, while the second term sets an upper limit on beam angular distribution, and r_0 is the maximum electron radius allowed by naturally occurring transverse field inhomogeneities in the undulator.

With present high energy accelerator technology, it has not been too difficult to meet the beam requirements stipulated in eq. (1). This has been demonstrated by FEL operation utilizing a variety of electron accelerators [1], including the modified electrostatic accelerator discussed here, which is presently being used to drive the University of California, Santa Barbara FEL [2]. In addition to producing coherent radiation in the far-infrared (FIR) region, two important innovations in electrostatic accelerator technology were achieved with the UCSB machine. First, a very low temperature, 1.25 ampere electron beam was produced using an electron gun matched to a standard National Electrostatic Corporation (NEC) high gradient accelerator tube for maximum charge transmission (100%) while minimizing geometric beam aberrations. Secondly, a substantial improvement in laser efficiency and electron pulse length was obtained as a result of electron beam recovery. Details of these experiments are discussed below.

Basic Characteristics of Electrostatic Accelerators.

Electrostatic accelerators generate continuous beams of very high quality electrons or ions having excellent voltage stability and small momentum spread. However, in their normal operating configuration, these devices produce beam currents ($I_b \leq 1$ milliampere) which are too low in intensity to drive FELs above treshold. Pulsing with a high current electron gun does not in itself solve this problem. The small capacitance of the terminal limits the amount of charge that can be extracted from it while keeping its voltage relatively constant in time. However, if a fraction of the beam current R is recovered and returned to the accelerator terminal, then the rate of voltage drop is reduced. The effective rate of voltage change can be calculated from:

$$\dot{V} = \dot{Q}/C = (I_b(1-R)-I_{ch})/C \qquad (2)$$

where I_{ch}, I_b, and C are respectively the accelerator charging current - typically a few hundred microamperes, the electron beam current - usually greater than 1 ampere, and the accelerator terminal electrical capacitance - about 200 picofarads. Since $I_{ch} \ll I_b$, eq(2) can be rewritten in terms of R and the rate of voltage drop $\dot{V}_{nr} = I_b/C$ produced when no beam is recovered

$$\dot{V} = \dot{V}_{nr}(1-R) . \qquad (3)$$

When the value of R approaches 1, more precisely when $R = 1-I_{ch}/I_b$, it may be possible for electrostatic accelerators to operate with a continuous, high current beam. With incomplete beam recovery, the accelerator can generate a quasi-continuous beam having a duty cycle given by

$$DC = I_{ch}/I_b(1-R) \qquad (4)$$

In addition to imposing quality requirements on the electron beam, FELs need long electron pulses to operate in an oscillator configuration. Starting from noise the UCSB FEL needs $T_s = 4$ microseconds for the oscillator to reach gain saturation. During this time, the energy of the electron beam cannot drop by more than that specified by the first formula in (1). This limitation is translated into a maximum acceptable rate of terminal voltage drop given by

$$\dot{V}_{max} = V/T_s 2N(1+mc^2/eV) \qquad (5)$$

where V is the initial terminal voltage. Combining equations (3) and (5), a critical recovery fraction R_c can be defined by the relation

$$R_c = 1- \dot{V}_{max}/\dot{V}_{nr} \qquad (6)$$

For values of $R \leq R_c$, the FEL will not be able to reach gain saturation. Table II summarizes beam requirements for the present UCSB FEL.

Table I. Elect. Beam Requirements for the UCSB FEL

Beam Voltage	3	MeV
Beam Current (Ib)	1.25	Amp
Maximum charging current(Ich)	200	μAmp
Terminal capacitance (C)	200	pf
Value of gama ( )	7	
Number of magnet periods (N)	160	
$\frac{\Delta\gamma}{\gamma}$ max	3.125	x 10-3
θ max	11.3	mrad
r_0	2.7	mm
Maximum emittance ($r_0 \theta_{max}$)	30	mm-mra
T_s	4	μsec
$\dot{V}_{nr}$	6.25	kv/ μsec
$\dot{V}_{max}$	2.74	kV/ μsec
R_c	0.56	

Experimental Apparatus

Phase I.

Development of the UCSB FEL has progressed through two phases. During phase I, a demonstration of electron beam recovery was carried out using a 3 MeV electrostatic accelerator located at the National Electrostatic Corporation plant in Middleton, Wisconsin. Figure 1 illustrates the position of important components inside the accelerator tank. The electron gun electrical design is shown in figure 2 while a few electron trajectories inside the electron collector have been drawn in figure 3. Table II summarizes design parameters for the electron gun and electron collector. Figure 4 shows various electronic signal inside the high-voltage terminal.
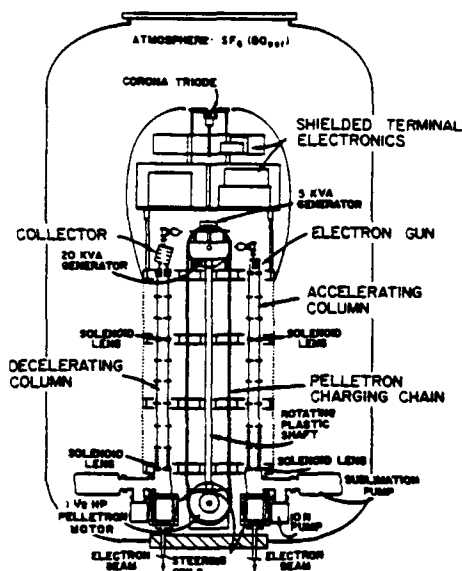
Figure 1. Major Accelerator components.

Table II. Electron Gun and Collector Design Parameters.

Gun		
Cathode (Dispenser)		
Diameter	15.2	mm
Perveance	0.24	μperv
Beam Area Compression Ratio	1	
Maximum Anode Voltage	50	kV
Grid Voltage		
beam on	Anode voltage/5	
beam off	-2	kV
Collector		
Number of stages	4	
Decelerator voltage	40-50	kV
Beam voltage spread acceptance	10	kV

To minimize geometrical aberrations inside the gun, a Pierce configuration, with low beam area compression, was used. Electrostatic focusing inherent in each accelerator section allows for optimum beam transmission through the 180 cm long accelerator tube without the need of introducing additional external beam focusing.
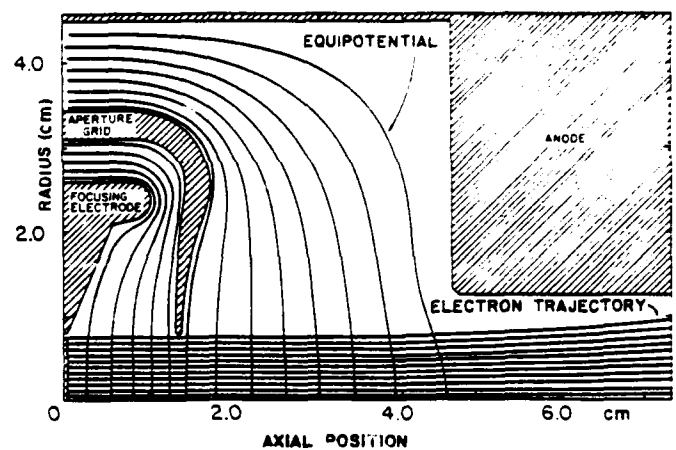

Figure 2. Electrical design of the UCSB electron gun.

Measurements of the electron gun emittance were carried out at Hughes Aircraft Corporation, at their Electron Beam Dynamics facility. Figure 6 shows the growth of beam radius (3dB) as a function of distance from the gun anode. From this data the normalized beam emittance was calculated. Results are presented in Table III.

The first beam recovery measurements began in 1982 using the simple beam transport arrangement shown in figure 7. The value of beam recovery ratio was obtained from measurements of the rate of terminal voltage decay $\dot{V}$, V_{nr} and equation (3). Also, beam quality measurements at 2.5 MeV were conducted in collaboration with NEC, Fermi Lab. and the University of Wisconsin [3]. A technique similar to that used with the electron gun was used to measure the emittance at high voltage. All these results have been included in table III.
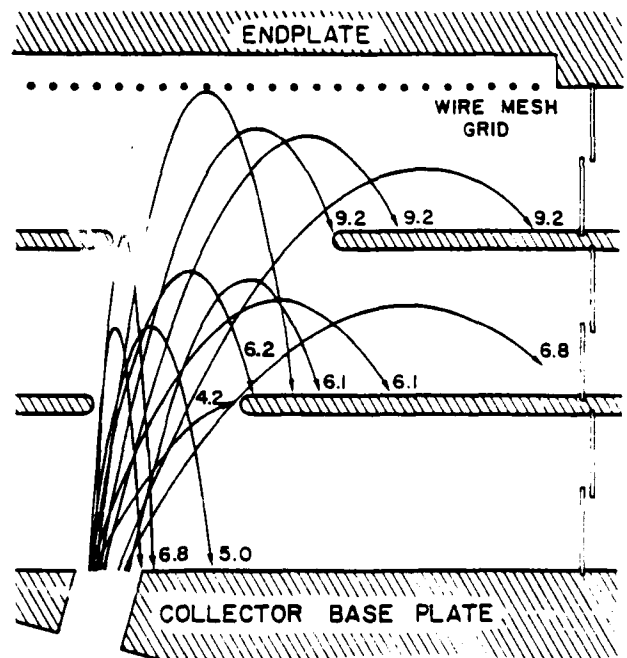

Figure 3. Multistage Depressed Collector. Electron trajectories are shown for various angles of injection and energy.
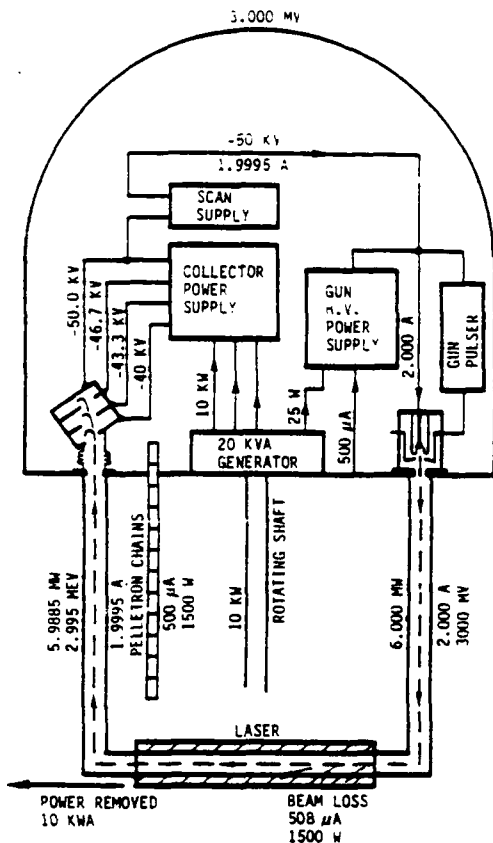
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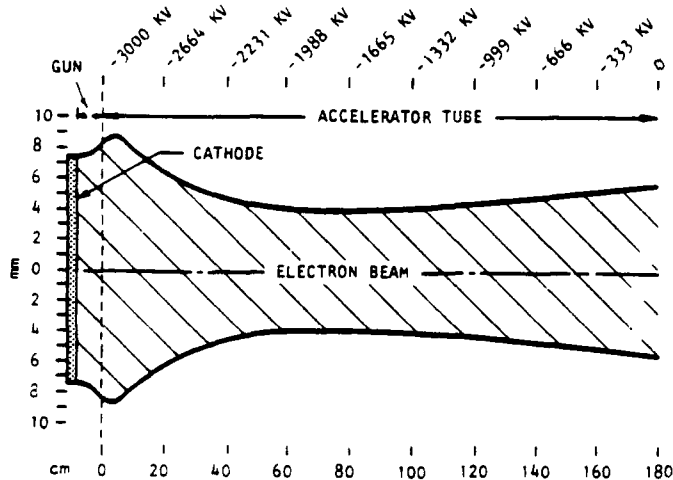**Figure 4. Terminal and accelerator electronics**

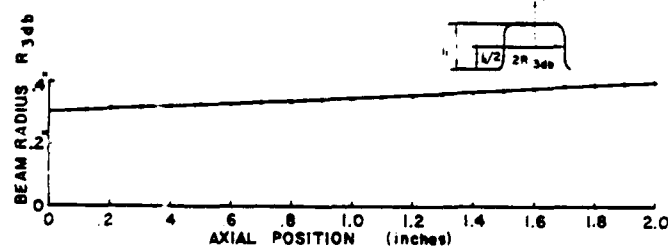**Figure 5. Beam envelope radius as a function of position inside the electron gun and accelerator tube.**

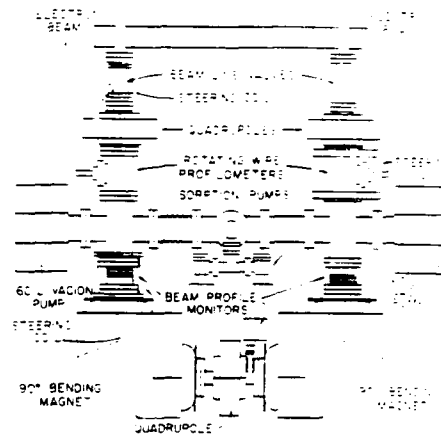**Figure 6. Beam envelope growth at V = 10 kV.**

Figure 7. Beam recovery apparatus for Phase I.

Phase II.

Implementation of research phase II began in early 1983 at UCSB, in a laboratory specially constructed for the FEL project, and culminated in the demonstration of laser oscillations in the FIR region in August, 1984. An illustration of the apparatus is shown in figure 8. The rectangular layout shows 5 achromatic corners, each consisting of a pair of 45^0 dipoles and a quadrupole, forming a 90^0 achromatic bend. Additional quadrupoles are used to provide beam matching in and out of the FEL magnetic undulator. The complete design includes ten 45^0 bending magnets, seventeen quadrupoles magnets, and 24 pairs of steering coils. Thirteen fluorescent screens, ten four-quadrant SEM foils and four current measuring toroidal coils were used as electron beam diagnostics. Capacitive pickup plates monitored terminal voltage change, permitting very accurate beam recovery measurements.
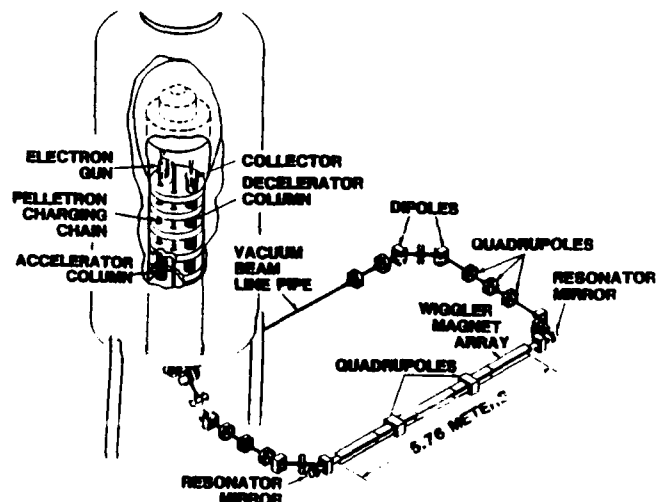

Figure 8. Illustration of the UCSB FEL apparatus.

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Experimental Results

Beam recovery and beam emittance results have been summarized in Table III below. A source of beam emittance is the gun cathode. At temperature T the cathode normalized emittance (can be calculated from the following formula [4]:

$$\epsilon_{Th} = D\sqrt{kT/mc^2} \qquad (7)$$

where D is the cathode diameter. The value of T for the UCSB electron gun is 1150 °K. Also, the empirical relation of Lawson-Penner

$$\epsilon_{LP} = 100\ \sqrt{I}\ \ \ \text{mm-mrad} \qquad (8)$$

relating beam emittance to beam current has been evaluated for the UCSB electron beam. This value as well as the theoretical thermal emmitance value has been entered in Table III for comparison.

Table III Experimental Results

Beam Recovery (Phase I)

Beam voltage	2.5	MV
Beam current	1.25	Amp
R (Maximum measured)	99.4	%
V̇ (")	37.5	V/ μsec

Beam Recovery (Phase II)

Beam voltage	3.0	MV
Beam current	1.25	Amp
Laser off:		
R (Max)	97	%
V̇ (")	187.5	V/ μsec
Laser on:		
R (Max)	95	%
V̇ (")	312.5	V/ μsec

Normalized Beam Transverse Emittance

Measured		
Electron Gun		
(V= 10 kV, I = 240 mAmp)	13.5 ± 5.4	mm-mrad
Elect. Gun + Elect. Acc.		
(V= 2.5 MV, I = 1.2 Amp)	7.5 ± 1.8	mm-mrad
Calculated		
Thermal	10	mm-mrad
Lawson-Penner	104	mm-mrad

From the experimental results shown in Table III the following conclusions can be drawn: a) Beam recovery using electrostatic accelerators can be quite efficient, b) well designed electron guns can generate electron beams with emmitance value close to the thermal theoretical limit, c) electrostatic accelerator tubes, such as the ones developed by NEC, provide beam acceleration without increasing beam emittance, and d) the beam quality of the UCSB FEL is much better than that required to operate it. Finally, overall laser efficiency improves with beam recovery. Typically, a FEL will extract an amount of power IV/2N from the beam when the laser reaches gain saturation. With beam recovery the amount of beam power loss is (1-R)IV . Thus, the efficiency of the laser can be written as follows:

$$\text{efficiency} = 1/(1+(1-R)2N) \qquad (8)$$

With a beam recovery value R = 0.95 the laser efficiency is about 5.3 %, which is a factor of 18 improvement over the efficiency that would have been obtained if no beam had been recovered.

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